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Modeling the Gulf Stream system: how far from reality?

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Abstract. Analyses of a primitive equation ocean model simulation of the Atlantic Ocean circulation at 1/6° horizontal resolution are presented with a focus on the Gulf Stream region. Among many successful features of this simulation, this letter describes the Gulf Stream separation from the coast of North America near Cape Hatteras, meandering of the Gulf Stream between Cape Hatteras and the Grand Flanks, and the vertical structure of ternperature and velocity associated with the Gulf Stream. These results demonstrate significant improvement in modeling the Gulf Stream system using basin- to global-scale ocean general circulation models. Possible reasons responsible for the realistic Gulf Stream simulation are discussed, contrasting the major differences between the present model configuration and those of previous eddy-resolving studies.

Introduction

The Gulf Stream (GS) is one of the most energetic current systems in the world ocean, and is a dominant feature of the North Atlantic circulation. Description and understanding of the dynamics of the GS, the associated mcso-scale eddies, and their interaction with the large-scale circulation are fundamental to improving our understanding of the North Atlantic's general circulation and its role in regulating the Earth's climate.

Accurately simulating the GS system has been one of the most challenging tasks in ocean modeling (Semtner, 1995; McWilliams, 1996). Due to the complex interplay of the flow field and density stratification in the dynamics of the GS, a realistic simulation must accurately account for both wind and thermohaline forcings. Heretofore, even moderately high resolution (1/2° to 1/6°) basin- to global-scale primitive equation general circulation models have not been able to accurately capture the structure of the GS system. A common problem in these previous simulations has been an unrealistic separation of the GS from the coast of North America: the separation latitude occurs too far to the north and is accompanied by a much too strong antic yclonic (clockwise) circulation.

his letter presents the recent success in simulating the GS system with a basin-scale primitive. equation model. The horizontal resolution of this model is approximately 1/6°, i.e. between 15 and 20 km in the vicinity of the GS. After twenty-two years of integration the model simulation shows significant improvements over previous ccldy-resolving, basin- to global-scale calculations. In particular, the GS separation and its subsequent downstream meandering arc in good agreement with the available. observations. The vertical profiles of temperature and velocity fields associated with the. GS resemble those derived from ship-based measurements.

Model and Experiment Design

The experiment described here makes use of the Parallel Ocean Program (POP) developed at Los Alamos National Laboratory (Dukowicz and Smith, 1994). The mode] domain covers the Atlantic basin from 35°S to 80°N and from 100”W to 20°E. The water exchange processes across the artificially closed open boundaries are parameterized by 5° wide buffer zones in which the model temperatures and salinities are restored toward the seasonal climatology. The model is formulated on a spherical grid with horizontal resolution of approximately 1/6° (O. 1875° in longitude and 0.1843° in latitude), and 37 vertical levels.

The model has been integrated for a total of twenty-two years, consisting of three experiments that differ from each other in their surface forcings and initial conditions. The first experiment was integrated for ten years starting from the January temperature and salinity distributions derived from the Levitus (1982) climatology and zero current. The surface wind stress and heat flux were based upon the seasonal climatology (Hellerman and Rosenstein, 1983; Han, 1984), and the surface salinity was restored to the Levitus climatology. The second experiment was initialized with the solution from the end of the first experiment. The wind stress was based upon the ensemble monthly mean fields derived from the European Center for Mediun~-Range Weather Forecast (ECMWF) analysis, while the heat and salt boundary conditions were the same as in the first experiment. The second experiment was integrated for two years. The third experiment was initialized with the solution from the end of the second experiment. The surface heat flux was derived from the ECMWF analysis based upon Barnier (1995)'s formulation, while the wind and salt boundary conditions were the same as the second experiment, The third experiment was integrated for another ten years. Results from only the third experiment arc presented here.

Simulation Versus observations

The major success of the present study is the realistic GS separation from the coast of North America near Cape Hatteras. This is illustrated in Figure 1 of the sea surface height and surface current averaged over the last ten years of simulation during the third experiment. In comparison with the previous ccidy-resolving calculations, the Community Modeling Effort (CME) for example, the prc.sent model shows a number of improvements in the GS simulation. The permanent, closed, anticyclonic circulation in the Mid-Atlantic Bight as seen in the CME simulations (see Figure 5 in Beckmann et ai., 1994, and Figure 2 in Bryan et ai., 1995) is absent in the present study. As one can see from the instantaneous map of surface current shown in Figure 2, the angle of the GS separation from the coast of North America near 35°N and 75°W is quite realistic. However, an excessive number of cold core rings are found south of the GS. These

[Figure 1]

[Figure 2]

cold core rings propagate westward, and eventually interact with the GS near the separation point. During such interactions, the GS is pushed to the north of its mean position, leading to the s-light overshoot as seen in Figure 1. Another major improvement of the present simulation is that the simulated GS can be identified as a well-defined meandering jet between Cape Hatteras and the Grand Banks.

[Figure 3]

Figure 3 compares the observed and simulated GS path statistics. The observed GS position is subjectively determined from two-day satellite images of sea surface temperature during 1983-1986 (Lee and Cornillon, 1996). 'I'he simulated GS position is objectively determined based on the maximum gradient of sea surface height every three days during the last ten years of the third experiment. From Figure 3, it is seen that the simulated GS is generally within the observed envelope. The mean GS path is remarkably reproduced by the ocean model: the root-mean-square difference between the observed and simulated GS path is 0.44° (on the order of 50 km) computed-over 55°W-80°W. The biggest discrepancy for the mean GS path occurs at the trough of the first meander near 68°W. The observations show a permanent trough near this longitude. However, the simulated trough appears much deeper than the observations. The standard deviation of the GS path is relatively small near Cape Hatteras (35°N and 75°W) 0.33° for observations and 0.52° for the model simulation, suggesting a very stable GS separation there. The standard deviation increases dramatically after the separation point because of the meandering, and remains relatively constant downstream. Averaged over the region 55°W-80°W, the simulated GS path standard deviation is larger than the observed: 0.83° for observations and 1.14° for the model simulation. This large standard deviation in the simulated GS path can be partly attributed to our path detection algorithms which sometimes cannot distinguish cold/warm core rings from the GS.

[Figure 4]

Figure 4 compares the simulated vertical structure of temperature and velocity with the *in situ* profile measurements (Halkin and Rossby, 1985). Both the data and the model simulation are analyzed in the "stream coordinate" reference frame, In the model analysis, the origin of the stream coordinate is co-located with the maximum surface velocity and the downstream direction is determined as the direction of the maximum transport between O and 2 km along the 73°W transect. The observation is the average of 16 transections near 73°W during 1980-1983, while the model simulation is the ave.rage of 16 snapshots from the last ten years simulation during the third experiment. From Figure 4, it is seen that the simulated temperature and velocity structure. of the GS agree quite well with observations. The offshore tilt of the thermocline and the maximum velocity core is realistic. The simulated GS core speed is 125 cm s^{-1}, slightly less than the observed one of 150 cm s^{-1}. From the temperature section, it is clear that the model does not properly simulate the distribution of 18°C mode water at 73°W.

Discussions

Determining the reasons responsible for the improvements observed in the present simulation compared to previous experiments will require a more systematic exploration of model sensitivity and a more in-depth analysis of the dynamics of the GS region than are possible here. At this point we can only outline the major differences between the present study and previous experiments and conjecture as to their importance.

The horizontal and vertical resolutions used in the present study are the highest among the existing z-coordinate, eddy-resolving calculations. The initialization procedure is also unique in the present study. All the previous eddy-resolving calculations have been initialized with the solutions from lower resolution models that already have unrealistic representations of the GS near the separation point, In contrast, the present calculation was initialized with the" observed climatological hydrographic structure, and spunup at 1/6° resolution. It appears that a horizontal resolution near **1/6°** maybe barely adequate to properly resolve the GS but unable to correct for strongly biased initial conditions within the decadal time scale of typical eddy-resolving model integrations. The time required for a higher resolution model to correct for the biased initial conditions is presumably shorter (Bleck et al., 1995). The apparent sensitivity of the simulation to initialization indicates that the higher resolution and more accurate descriptions of the hydrography of the GS region (e.g., Lozier et al., 1994) should be used in future eddy-resolving calculations.

The selection of sur-face forcings also affects the. separation characteristics. Certain characteristics pertaining to the cyclonic wind curl distribution in the Western North Atlantic can be related to the separation of the GS, and arc found in the ECMWF operational analysis but not in the long-term climatology. A detailed exposition of the effect of different wind products on the simulated GS separation will be presented in a separate study (Gangopadhyay and Chao, Dynamical impact of cyclonic wind stress curl on GS separation, submitted to Dyn. Atmos. Oceans, 1996).

Another new feature in the present study is the presence of the Green land-Iceland-Norwegian Seas and prognostic calculation of the exchanges between them and the Atlantic Ocean. Many previous calculations have northern boundaries near the sill in Denmark Strait. The inflow of deep water is crudely parameterized in a buffer zone through a relaxation of the solution toward the observed climatological conditions. It has been shown that the solution can be sensitive to the prescription of the hydrographic properties in this buffer zone (Döscher et al., 1994). It remains to be studied to what extent the overflow through the Denmark Strait is realistically represented in the present study, and what impact this has on the GS behavior. It is not known whether the presence of the Western Mediterranean Sea plays any role in simulating the GS system, though this seems less likely. The flee-surface formulation for the barotropic flow and the unsmoothed bottom topography may also improve the solution.

in summary, a horizontal resolution of at least 1/6° in both longitude and latitude seems to be a necessary condition to obtain a realistic representation of the GS. The. additional factors of finer vertical resolution, unbiased initial conditions, more realistic surface forcings and bottom topography all help to improve the accuracy of the solution, but may only become effective when the minimum horizontal resolution is achieved. Further experiments and more in-depth analysis of the present simulation will bc necessary to determine the relative importance of these factors in obtaining an accurate simulation of the GS system.

Conclusions

This experiment represents a significant improvement in the simulation of the GS system compared to the previous eddy-resolving calculations, Among many successful features of the simulation, this letter describes a realistic GS separation from the North American coast near Cape Hatteras, energetic meanders of the GS between Cape Hatteras and the Grand Banks, and realistic cross-sectional structure of the GS. The relatively good qualitative agreement of the present model simulation with observed GS structure has allowed us to begin to make direct quantitative comparisons with observations. These quantitative measures of model skill will facilitate. a more meaningful comparison of different experiments and models than has heretofore been possible.

Our preliminary comparisons have revealed some model deficiencies which can be further improved. For example, an excessive number of cold-core rings are found south of the GS. The simulation of the subtropical mode watt.r needs to be further examined and improved, Many other aspects of the basin-scale circulation remain to be examined in the present simulation. Ideally it is important to conduct many sensitivity experiments to explore the full range of model parameters, and to investigate the model response to various external forcings. Given the improvements found here in simulating the GS system and the continuous increase of computing power, wc believe that basin-scale eddy-resolving ocean models are finally approaching reality in describing both the time-mean large-scale and transient mcso-scale circulation.

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Figure 1. Climatological annual-mean maps of (top) sea surface height and (bottom) surface current simulated by the. present model averaged over the last ten years of the third experiment. The contour interval is 10 cm.

Figure 2. Instantaneous map of surface current simulated by the present model on October 18 of year 16.

Figure 3. The observed and simulated Gulf Stream path statistics. The black solid line represent the observed mean path, and the black dot lines represent the observed envelope. The red solid line represents the mean path derived from the present model. The corresponding standard deviations of the Gulf Stream path are also shown.

Figure 4. The observed (a and b) and simulated (c and d) temperature and downstream velocity calculated in the stream coordinate system. The contour interval is 1°C for temperature, 10 cm s^{-1} for velocity less than 100 cm s^{-1} and 25 cm s^{-1} otherwise;

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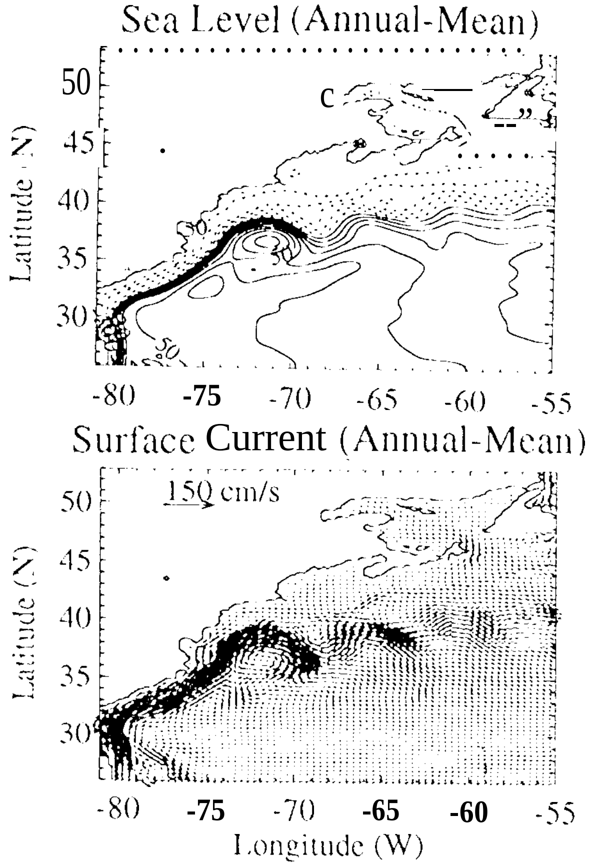

Figure 1

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Surface Current (Oct.18, Year 16)

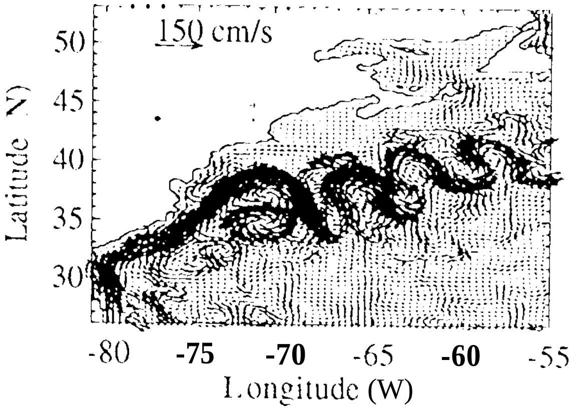

Figure 2

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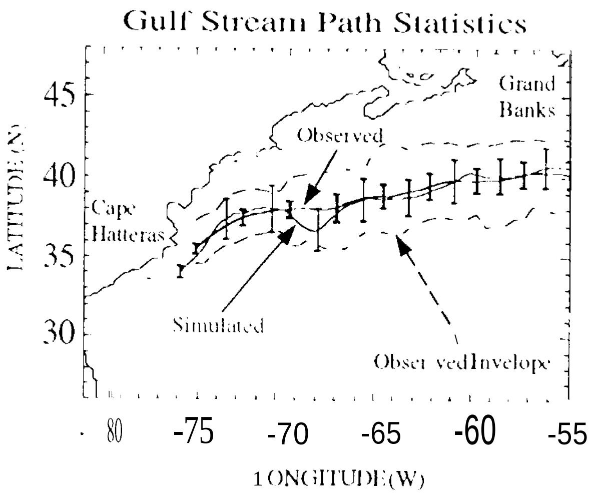
Gulf Stream Path Statistics
LATITUDE (N)
45
40
35
30
Grand
Banks
Observed
Cape
Hatteras
Simulated
Observed Envelope
-80
-75
-70
-65
-60
-55
LONGITUDE (W)

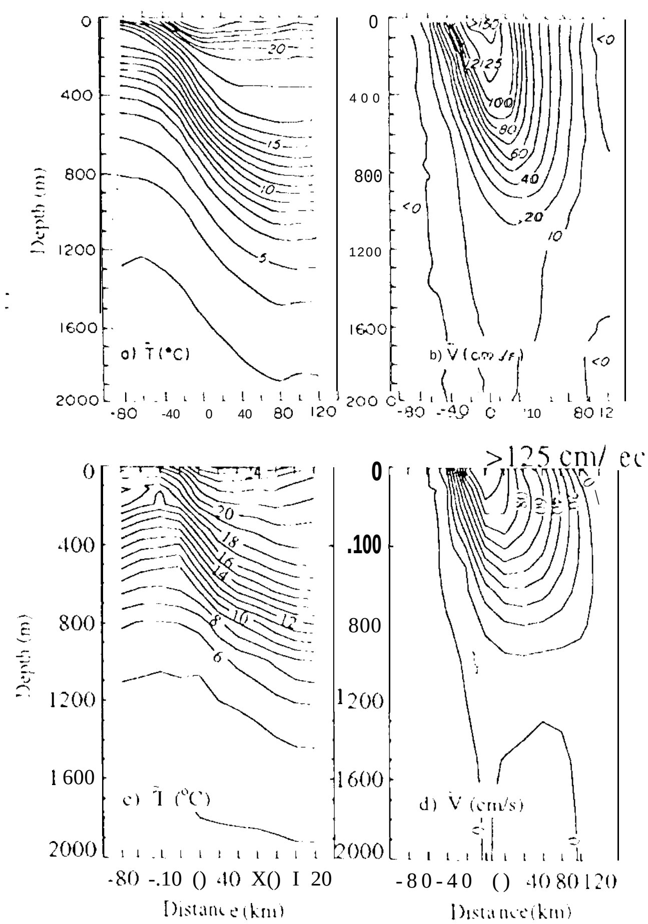

Figure 4
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